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STATISTICAL CHARACTERISTICS OF A TURBULENT FREE-CONVECTION FLOW IN THE ABSENCE AND PRESENCE OF A MAGNETIC FIELD

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Abstract—Recorded signals of temperature fluctuations in a mercury turbulent-free convection layer in the presence and absence of a magnetic field were analysed. The statistical quantities obtained from the analysis were the flatness, skewness and intermittency factors.

The distributions of these statistical quantities indicate the presence of large vortex structures in the layer and their strong participation in the mixing and transfer flow mechanisms. Also, there is evidence that a drastic change in the large scale structures occurs at transition, caused by the presence of the magnetic field.

NOMENCLATURE

B, magnetic flux density;
$f(\Theta')$, probability density distribution;
K, flatness factor,

$$\left(K = \frac{\int_{-\infty}^{+\infty} \Theta'^4 f(\Theta') \mathrm{d}\Theta'}{(\sqrt{\overline{\Theta'^2}})^4} \right);$$

M, Hartman number (defined in [2]);
Ra, Rayleigh number (defined in [2]);
S, skewness factor,

$$\left(S = \frac{\int_{-\infty}^{+\infty} \Theta'^3 f(\Theta') \mathrm{d}\Theta'}{(\sqrt{\overline{\Theta'^2}})^3} \right);$$

x, y, coordinates along and normal to the vertical wall.

Greek symbols

γ, intermittency factor (fraction of time during which the flow remains turbulent);
Θ', turbulent temperature fluctuations.

INTRODUCTION

THE RESULTS of an investigation concerning the structure of a turbulent free-convection thermal layer of an electrically conducting fluid (mercury), were reported in two previous communications [1, 2]. In these experiments the thermal-boundary layer was formed along an isothermally-heated vertical wall of a stainless steel cell filled with mercury. The experimental set-up and measuring techniques were described in [1].

The results of the measurements conducted in the absence of a magnetic field are discussed in paper [1] while the changes in the structure of the layer, due to the applied magnetic field, are described in [2].

In the absence of the magnetic field the measurements indicated that the general structure of the free convection layer was similar to that of a conventional boundary layer, consisting of a wall-influenced inner part and an outer part which resembles a free turbulent flow. However, a comparison of the measured temperature turbulent-intensity distributions with those obtained in free and mixed turbulent convection over heated horizontal surfaces [3–5] showed that the scales characterizing the former case are different than those of the latter cases. Among the factors which possibly contribute to these differences are the existence of organized vortex motions observed by several investigators in free convection layers along vertical plates [6–8] and the influence of the geometry of the cell on the structure of turbulence. In the presence of a magnetic field, normal to the flow, it appears that up to a certain value of the parameter Ra/M there is little change in the turbulent structure. Beyond this value, which corresponds to the onset of transition from turbulent to laminar flow, a rapid drop in the turbulent intensity with increasing magnetic field as well as drastic changes in the structure of turbulence occur.

In the present paper the results of a further investigation of the statistical characteristics of the turbulent temperature field are reported. This investigation should provide a deeper understanding of the structure of turbulence and the inflence of a magnetic field on it.

MEASURED QUANTITIES

As already mentioned [1, 2] turbulent temperature fluctuations, corresponding to different locations in the layer, were picked up by a platinum resistance sensor (quartz-coated hot-film probe) and recorded on a magnetic tape. On processing these recordings the skewness factor, S, flatness factor, K, and intermittency, γ, were obtained for both the non-magnetic and magnetic cases.

To calculate the skewness and flatness factor, the probability density distribution, $f(\Theta')$, of the temperature fluctuations was first obtained, by using a Federal Scientific UC201 correlator. Subsequently, a computer program was used for the computation of the third and fourth central moments of the fluctuating temperature, that is the skewness and flatness factors as defined in the nomenclature.

Essentially, intermittency measurements consist of counting time periods of turbulent fluid motion. Although, in principle, it is easy to define a turbulent motion, the existing experimental techniques for the identification of the flow character involve subjective decisions; therefore, they contain a certain degree of arbitrariness. These techniques extend from film-strip records inspection [9] to application of electronic methods of treatment of the turbulent signal [10, 11] and recently, to methods based on digital sampling [12, 13]. A critical analysis of the turbulent–non-turbulent decision methods has been presented in [14]. As mentioned in this reference, the simplest method of detecting turbulence is by identifying its small scale structure. This requires emphasizing the high frequency components of the spectrum either by differentiation or high-pass filtering of the signal.

In the case of the interface between cold–hot regions, there are several works describing measurements of intermittency [15–17]. Also, when temperature differences are small, in which case heat can be considered as a passive scalar, thermal intermittency has been used to define the laminar–turbulent interface in free turbulent flows [18, 19].

In the present work intermittency was measured from direct recordings of the temperature fluctuations. The details of the applied procedure are as follows. As mentioned above, temperature fluctuations were recorded on a magnetic tape at each measuring location in the thermal layer. To measure intermittency the recorded signal was played back and displayed to a tectronix oscilloscope. Subsequently, a series of photographs were taken for each particular case and the intermittency factor was measured by direct inspection of the photographed signals. The application of this method in the case of free convection in the cell, presented some particular problems for the following reasons.

The bulk of the fluid between the two thermal layers, formed along the opposite walls of the cell, is itself in a state of irregular motion which consists of buoyancy driven, rising lumps of fluid. These large-scale convective motions, which might be irrotational, have also been detected in the thermal layer since they produce long period signals which were observed in the recordings. Due to the described flow conditions in the cell it is not possible to define a thermal layer turbulent–non-turbulent interface. Also the convective large scale motions make the distinction between turbulent and non-turbulent parts of the signal more difficult, especially at the outer part of the layer or in the presence of large magnetic fields where long period signals dominate. This probably results in an increase of arbitrariness in deciding on the flow character. To minimize errors and reduce arbitrariness, intermittency at each point in the layer was obtained as an average of values measured at several different parts of the recorded signal.

Experimental errors in measuring the parameters x, y, and Θ', have been discussed [1, 2]. From the measured statistical quantities intermittency values are suspected of including a higher percentage of error, because of the subjectiveness involved in these measurements. The magnitude of this error was estimated from standard deviation calculations. It was found that it varied from 3% near the wall to about 10% in the outer part of the layer. This should be expected since, as already mentioned, arbitrariness in measuring intermittency increases in this part of the layer.

The results of flatness and skewness measurements are shown in Figs. 1–4 while intermittency measurements are given in Figs. 5–7. The applied power in this experiment was 1300 W.

DISCUSSION OF THE RESULTS—CONCLUSIONS

The flatness and skewness factor distributions measured at various locations along the plate in the absence of a magnetic field are shown in Figs. 1 and 2.

For homogeneous turbulent flows, the probability distribution function of the fluctuating velocity field is joint-normal, corresponding to the values of zero for skewness and three for flatness [21]. Although the reasons for the departure from these values in the case of non-homogeneous turbulent velocity fields are due to the non-linearity of the equations of motion, the nature of the departures are not fully understood at present [21].

In general, deviations of the flatness factor from the value of three are related to inhomogeneities in the flow. Abnormally high values of flatness indicate a spotty character of the turbulent intensity with alternates of long period fluctuations and rapid fluctuations of high intensity. The existence of homogeneity in a turbulent field is associated with randomness in turbulent motion, while inhomogeneity indicates the presence of organized motions in the flow. It is known that such motions in the form of large-scale vortex structures dominate many of the turbulent shear flows [22]. For instance, in the case of the turbulent wake behind a cylinder measurements of the flatness factor corresponding to the components of the turbulent velocity along the principal directions of the mean rate of strain, exhibit a rapid increase towards the edges of the wake [21, 23]. Since these velocity components are closely associated with the Reynolds stresses, it was suggested that high values of the flatness factor are related to inhomogeneities of the shear stresses. This is probably caused by the presence of large scale organized motions detected in the wake [24–27].

The physical meaning of the skewness factor in the case of a turbulent velocity field is generally associated with the convection of turbulent energy from regions of high intensity to regions of lower intensity [21]. In the case of a turbulent temperature field, negative values of the skewness factor measured at a given location, indicate that turbulent eddies cooler than the

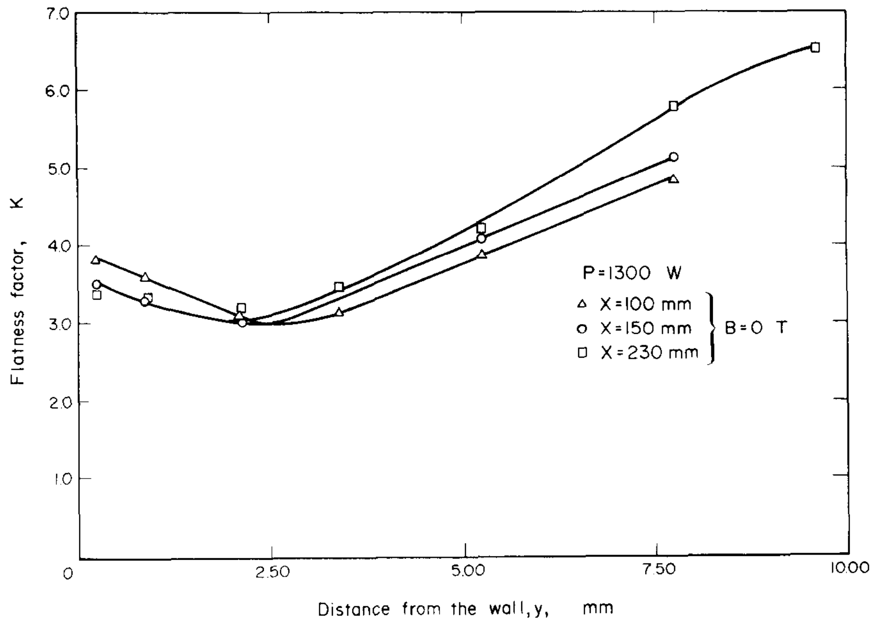

FIG. 1. Flatness factor distributions at different locations along the plate in the absence of a magnetic field.

mean temperature are crossing this location more often than hotter eddies. The opposite conditions prevail when the measured values of the skewness factor are positive [28].

Based on the preceding discussion, it is possible to proceed in the interpretation of the measurements obtained in the present experiment. The distribution of the flatness factor presented in Fig. 1 indicates that the turbulent temperature field is homogeneous within a region located at a distance of approximately 2.5 mm from the wall. Temperature intensity measurements presented in [1] show that this location corresponds to that of maximum intensity.

The slight deviation from homogeneity which appears to occur in the inner part of the layer is probably due to the proximity of the wall. At the outer part of the layer the flatness factor increases rapidly, obtaining high values in the proximity of the layer's edge in a way similar to that observed in the turbulent wake. Therefore, it is plausible to suggest that the increasing inhomogeneity of the turbulent field, indicated by the high values of the flatness factor in this region is caused by the presence of large scale motions. These structures, which have been observed by several investigators in the transition region of free-convection turbulent layers along vertical heated plates, appear to persist further downstream, influencing the turbulent processes in the layer. Further, it can be suggested that the rotation of these vortices produces a transfer of small eddies located in the inner hotter part of the thermal layer into the outer cooler part, while at the same time cooler eddies from the outer part are transferred into the inner region of the layer. This mixing mechanism explains the measured distributions of the skewness factor shown in Fig. 2 in which the inner region is characterized by negative values of the skewness factor while the outer part by increasingly positive values of this factor.

It has been implied (above) that the organized large scale structures, whose presence was inferred from the presented measurements, dominate the heat-transfer

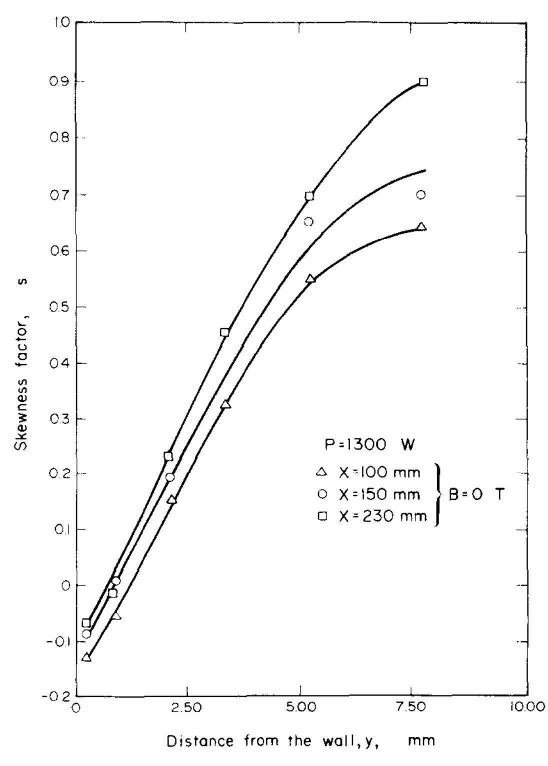

FIG. 2. Skewness factor distributions at different locations along the plate in the absence of a magnetic field.

processes in the thermal layer. Although further investigation is needed in order to establish these views, they offer a plausible explanation for the differences in the characteristic length scales of the previously-mentioned cases of turbulent convection flows. Namely, the presence or absence of organized vortex motions in the flow or differences in their structure and geometry might cause the observed variations in the characteristic length scales in the cases of turbulent free convection from horizontal and vertical plates and mixed convection from horizontal surfaces.

Intermittency is of interest because of its association with a number of phenomena occurring at the turbulent–non-turbulent interface of shear flows. These phenomena control the propagation of turbulence into the potential flow; that is the entrainment mechanism. This mechanism is responsible for the growth of the shear flows and probably closely related to the turbulent mixing in these flows. Furthermore, there is evidence that the occurrence of intermittency is not confined to the interface, but it is present everywhere in the flow. This indicates that intermittency might be a more general phenomenon related to the nature of turbulent motion.

In the absence of a magnetic field the obtained intermittency distributions show that the flow is intermittent even very close to the wall (Figs. 5–7). In this region, within or close to the laminar sublayer, a number of phenomena, such as turbulent bursting, which appear to play an important role in turbulent processes, have been observed recently [29, 30]. It could be possible that the observed intermittent flow pattern close to the wall is related to these phenomena. However, this is a conjecture since at the present time these phenomena are not well understood.

The influence of the existing circulatory motion in the cell and that of the test cell walls which may have on the large scale structures and the measured intermittency, will be discussed next.

The performed measurements of temperature distributions covering the entire width of the cell, revealed a flow pattern consisting of two layers of fluid moving in opposite directions along the vertical walls. The two thermal boundary layers, each approximately 10 mm thick, were well separated by an isothermal region of fluid occupying the central part of the cell. Although the presence of the magnetic field produced an increase in the thickness of the layers, they were found to remain separated in all cases examined. Based on this observation it can be concluded that the obtained measurements were not influenced by the circulatory motion in the cell.

In reference to the second question posed above it can be said that, since the thermal-layer thickness to test cell width ratio for this experiment is 1/7, the vortex structures in the layer could be influenced by the wall. However, this influence is not expected to change the nature of the physical processes related to the basic mixing and transfer mechanisms.

The influence of the applied magnetic field on the flatness and skewness factors is shown in Figs. 3 and 4. The flatness factor distributions show no change up to magnetic field intensities close to 0.7 T. This value approximately corresponds to transition conditions at this particular location of the layer [2]. Although the existing measurements cover only part of the outer region of the layer it appears that at higher magnetic field intensities the flatness factor attain a constant value of 4.5 through the layer. This is caused by a pronounced drop of the outer part of the distribution with a simultaneous rise of its inner part. Contrary to

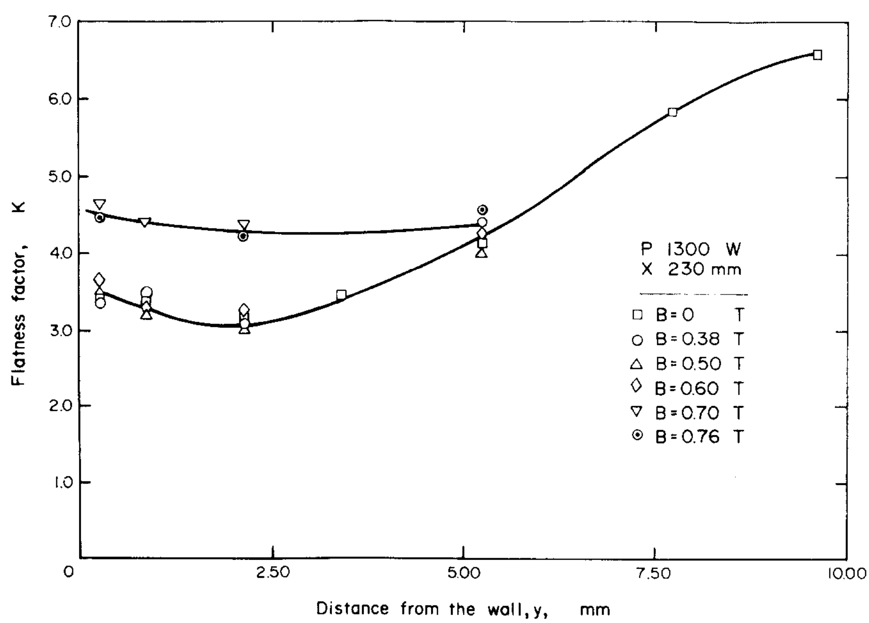

FIG. 3. Influence of the applied magnetic field on the flatness factor distributions.

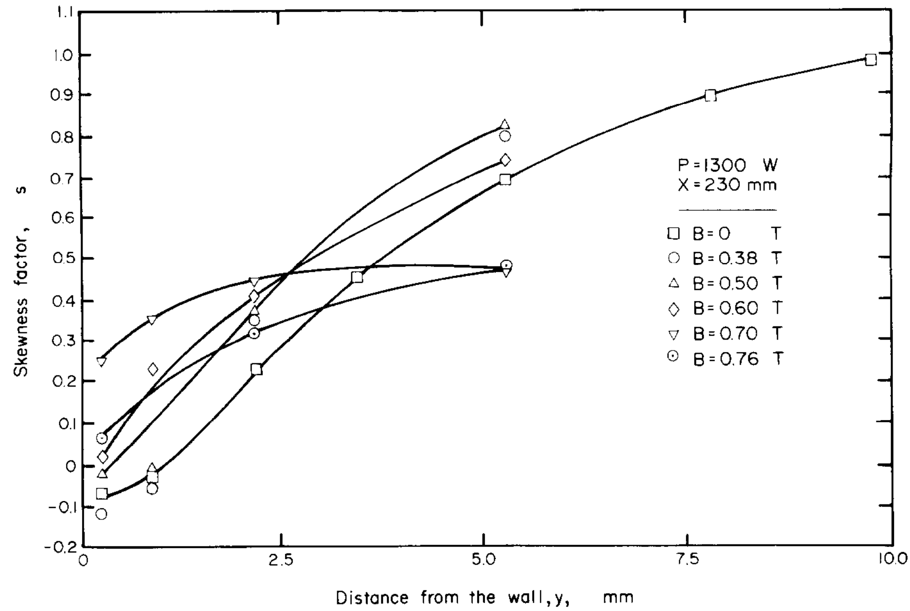

FIG. 4. Influence of the applied magnetic field on the skewness factor distributions.

the flatness factor, the skewness factor distribution changes continuously with increasing magnetic field, shifting generally towards higher values. However, here again, there is a distinctive change at approximately 0.7 T, similar to the one observed in the flatness factor distribution.

In the preceding discussion of the non-magnetic case, an attempt was made to interpret the measured flatness and skewness distributions in relation to the presence of large scale organized structures in the layer and to describe a possible mixing and transfer mechanism. The presented experimental evidence, although insufficient, offers some valuable information regarding the effect of the magnetic field on the large scale structures and the transfer processes related to them. A discussion on this information follows.

The observation that the flatness factor distribution remains unchanged up to magnetic field intensities close to 0.7 T indicates that the organized large-scale structures persist until the onset of transition in the layer. On the other hand, the corresponding change in the skewness factor distribution suggests that both the large scale structures and the smaller size turbulent eddies are influenced by the magnetic field. Indeed, the magnetic field is expected to slow down the large-scale vortex motion and also, to suppress the smaller scale turbulence. These effects cause a reduction of turbulent mixing and transfer, resulting in a 'hotter' thermal layer. The slow down of the large scale vortex motion is probably responsible for the gradual elimination of the negative part of the skewness factor distribution observed in the non-magnetic case. Also, the shift of the skewness distribution could be attributed to higher temperatures prevailing in the layer in the presence of the magnetic field. Finally, the drastic changes in both distributions near transition indicate corresponding drastic changes in the large scale structure.

In the presence of a magnetic field the intermittency distributions (Figs. 5–7), indicate the following.

Consistent with the experimental results presented in this work and also in [1 and 2], the intermittency factor distributions show a pronounced change at magnetic field intensities corresponding to transition. This is a further indication that the large scale structures undergo drastic changes related to transition in the layer. It should also be noticed that intermittency increases faster near the wall with increasing magnetic field. This further supports the suggestion expressed in [2] according to which the laminar sublayer expands with increasing magnetic field.

The information obtained from the experimental results is not sufficient to provide a clear and complete understanding of the structure of the turbulent free-convection layer. However, it provides further evidence in support of the presence of large-scale vortex

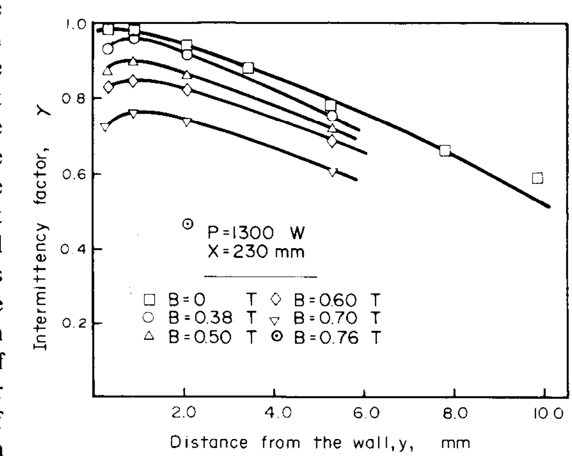

FIG. 5. Intermittency factor distribution in the absence and presence of the applied magnetic field.

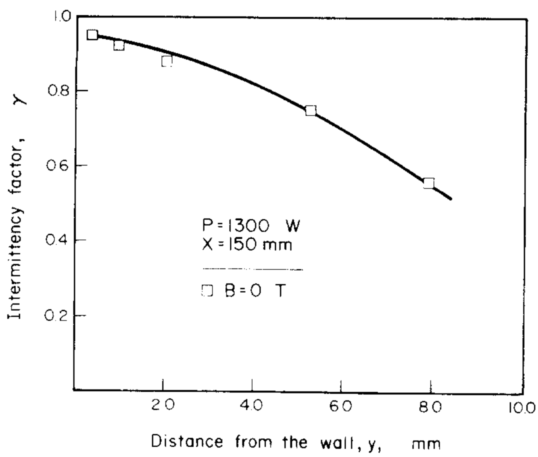

FIG. 6. Intermittency factor distribution in the absence of a magnetic field.

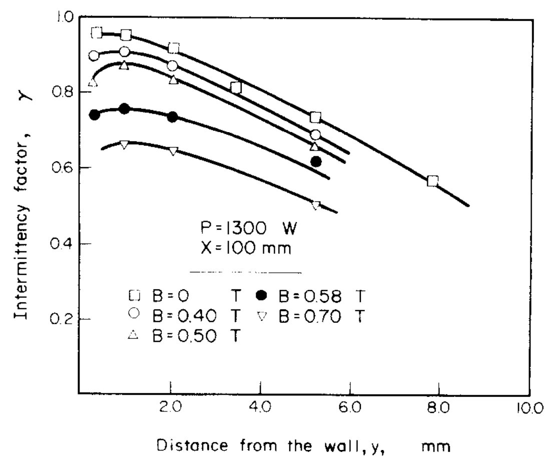

FIG. 7. Intermittency factor distribution in the absence and presence of the applied magnetic field.

motions in the layer. It also supports the view that the presence and particular structure of these motions dominate the mixing and transfer mechanisms in turbulent heat-convection flows and defines their characteristic scales. Furthermore, there are indications that transition in the presence of a magnetic field is related to drastic changes in these vortex structures.

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CARACTERISTIQUES STATISTIQUES DE LA CONVECTION NATURELLE TURBULENTE EN L'ABSENCE OU EN PRESENCE D'UN CHAMP MAGNETIQUE

Résumé—On analyse des enregistrements de fluctuations de température dans une couche de mercure en convection naturelle turbulents en présence ou en l'absence d'un champ magnétique. Les grandeurs statistiques obtenues sont les facteurs d'aplatissement, de dissymétrie et d'intermittence. Les distributions de ces grandeurs statistiques indiquent la présence de grandes structures tourbillonnaires dans la couche et leur forte participation au mélange et au transfert. Elles montrent aussi un changement important des grandes structures à la transition, causé par la présence du champ magnétique.

STATISTISCHE CHARAKTERISTIKEN EINER TURBULENTEN FREIEN KONVEKTIONSSTRÖMUNG MIT UND OHNE ANWESENHEIT EINES MAGNETFELDES

Zusammenfassung—Aufgezeichnete Signale von Temperaturschwankungen in einer turbulenten freien Konvektionsschicht in Quecksilber mit und ohne Anwesenheit eines Magnetfelds wurden analysiert. Die statistischen Größen, die aus der Analyse erhalten wurden, waren Blockkoeffizienten, Schiefe und Intermittenzfaktoren. Die Verteilung dieser statistischen Größen wiesen auf die Anwesenheit großer Wirbelstrukturen in der Schicht und ihre starke Beteiligung an den Misch- und Transportströmungsmechanismen hin. Es zeigt sich auch, daß beim Übergang, der durch die Anwesenheit des Magnetfeldes erzeugt wird, ein drastischer Wechsel in den großräumigen Strukturen auftritt.

ВЛИЯНИЕ МАГНИТНОГО ПОЛЯ НА СТАТИСТИЧЕСКИЕ ХАРАКТЕРИСТИКИ ТУРБУЛЕНТНОГО СВОБОДНОКОНВЕКТИВНОГО ТЕЧЕНИЯ

Аннотация — Анализируется влияние магнитного поля на температурные флуктуации в турбулентном свободноконвективном слое ртути. В результате анализа определены такие статистические величины, как эксцесс, асимметрия и коэффициент перемежаемости. Распределение этих статистических величин указывает на наличие больших вихревых структур в слое и их большое влияние на процессы перемешивания и переноса в потоке. Показано также, что магнитное поле вносит сильное изменение в характер крупномасштабных структур в переходной области.